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A NONCONTACTING DISPLACEMENT MEASURING TECHNIQUE AND ITS APPLICATION TO CURRENT VIBRATION TESTING

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PART I - INSTRUMENTATION TECHNIQUE

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INTRODUCTION

Many structural research investigations require the measurement of displacement amplitudes over the surface of excited models. Complex and fragile models have required the use of noncontacting transducers but they have limited range and sensitivities that vary with average pickup height. In this paper I will describe an instrumentation technique for measuring the vibration amplitude over the surface of a model in the presence of unknown irregularities, describe the method of calibration, and show a scheme for extending the range of noncontacting transducers. I will also show a technique used to determine the direction of the displacement with reference to the vibration of any point on the model. The analog voltage representation of the vibration may be used in ways to suit the test program and will be discussed by Mr. Naumann following this presentation.

SERVOCONTROLLED TRANSDUCER

Figure 1 is an overall pictorial and block diagram of the servocontrolled transducer. Ignore any parts not mentioned here as they are not required to understand the operation. When there is no vibration by the structure, and the transporting carriage is moved along the track, the transducer takes positions above the structure as seen in figure 2. Notice that the transducer assumes a position a fixed distance from the surface of the structure. The position taken by the transducer when the structure is excited is the same as when there is no vibration. The initial pickup height is manually set at the center of the linear range of the transducer using the dc offset voltage. The output of the dc offset combines with the transducer output to produce zero potential at the operational amplifier. Any change in pickup height will result in a dc voltage at the operational amplifier. This dc voltage causes the servomotor to rotate and position the pickup back to the height set with the dc offset. The low-pass filter blocks the oscillating components, so the transducer is controlled by dc signal components. The low-pass filter has a cutoff at about 5 Hz, thus the transducer will track or follow irregularities from any source below 2 Hz. Rate feedback was obtained using a small stock dc motor as a tachometer; it was connected directly to the armature of the servomotor after removing a back plate.

CALIBRATION AND RANGE EXTENSION

The differential transformer serves as a convenient calibrating device and aids in obtaining displacement measurements beyond the ordinary range of noncontacting transducers. A calibration of the noncontacting transducer is easily obtained using its voltage analog of deflection and the differential transformer's voltage analog of transducer height. The dc offset is used to move the noncontacting transducer over the calibrating range and the distance traveled is monitored at the differential transformer converter output. If the low-pass filter is replaced by a rectifier filter, the vibration amplitude will control the transducer height and the differential transformer will provide a voltage analog of the height. The difference between the height when the structure is at rest and the height when excited is a measure of the amplitude of the vibration.

VOLTAGE ANALOG PHASE RELATIONS

Excited structures with standing vibrations have deflections that are in phase or in opposite phase to the excitation. In order to provide this phase information a ring demodulator is employed. Figure 3 shows the circuit used to provide a dc voltage having a polarity that identifies the in phase or opposite phase condition. The ac-dc converter is phase insensitive; however, by adding the circuitry shown the signal may be displayed having a positive polarity when in phase and negative polarity when at opposite phase to the reference. A phase sensitive ac to dc converter could eliminate this item.

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PERFORMANCE

A representative plot of the performance of this instrument is shown in figure 4. The continuous curve is a calculated normalized plot of the deflection of a fixed-fixed beam excited in the third mode. Superimposed on the plot are recorded data from a similar beam normalized and recovered from an XY plotter. There was similar agreement for three other modes tested.

CONCLUDING REMARKS

The instrument technique described in this paper allows an investigator to rapidly measure displacement amplitudes on fragile and irregular shaped structures in the presence of low-frequency disturbances.

Structural research investigators can use this technique and the resulting data may be displayed in interesting formats. One of the test facilities that has applied this technique to their investigations is the Dynamic Loads Division, and Mr. Naumann will next cover former and current applications and data display formats.

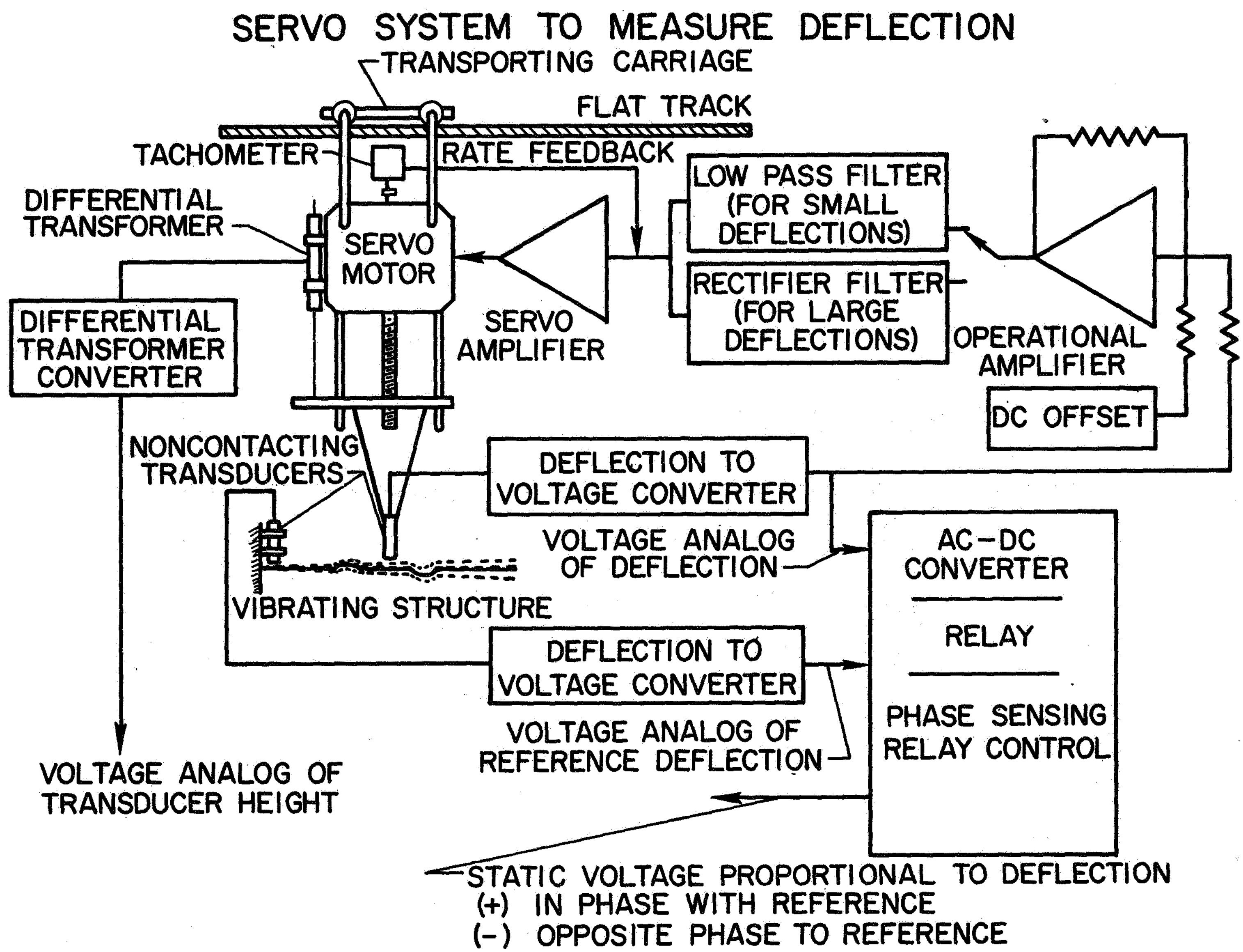

Figure 1.- Pictorial and block diagram of servocontrolled transducer and associated components.

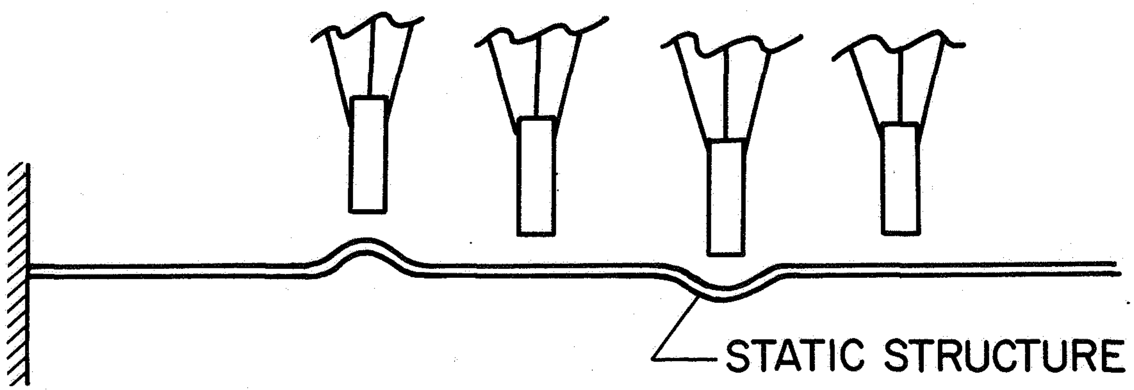

Figure 2.- Transducer position at four locations.

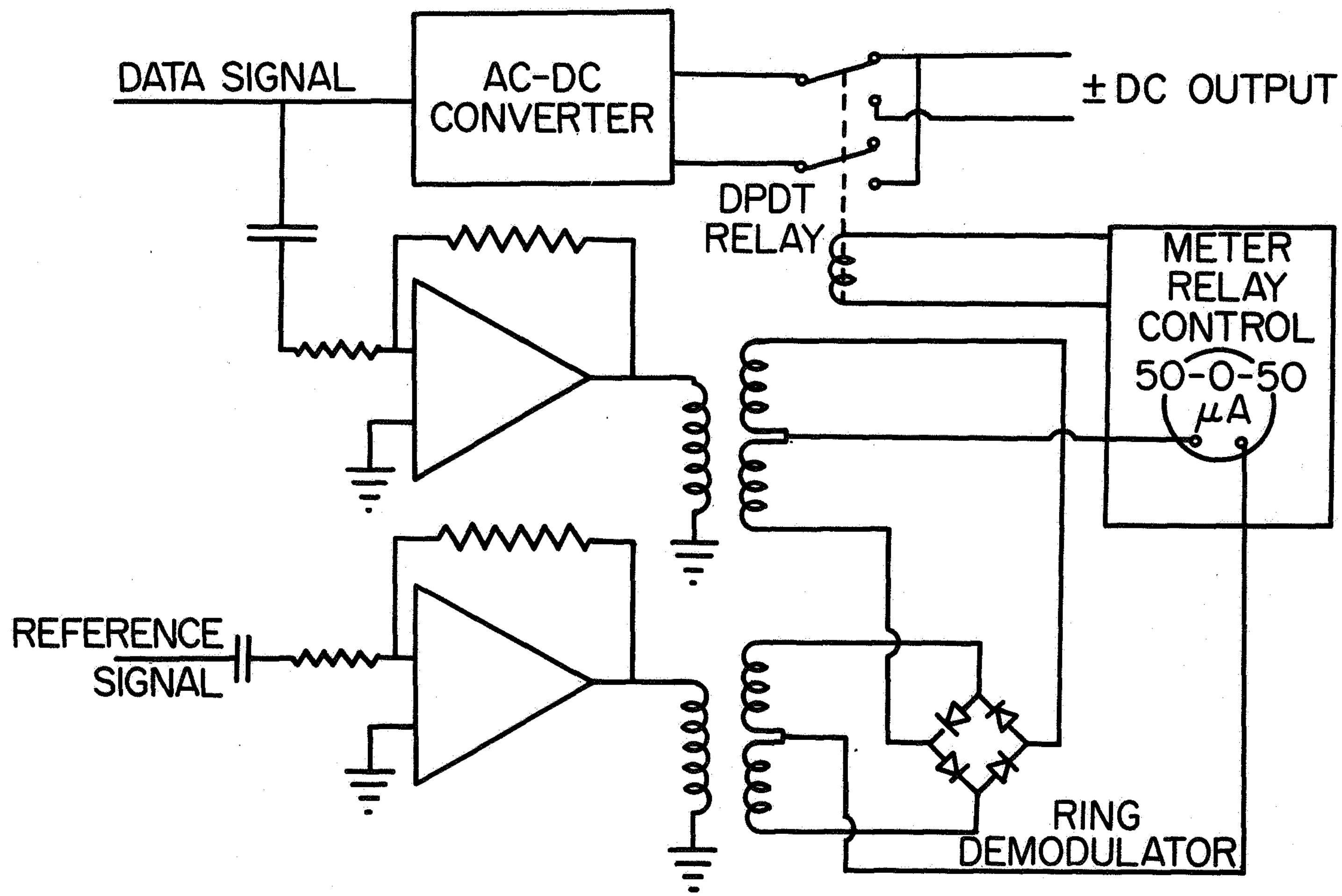

Figure 3.- Phase sensing instrumentation.

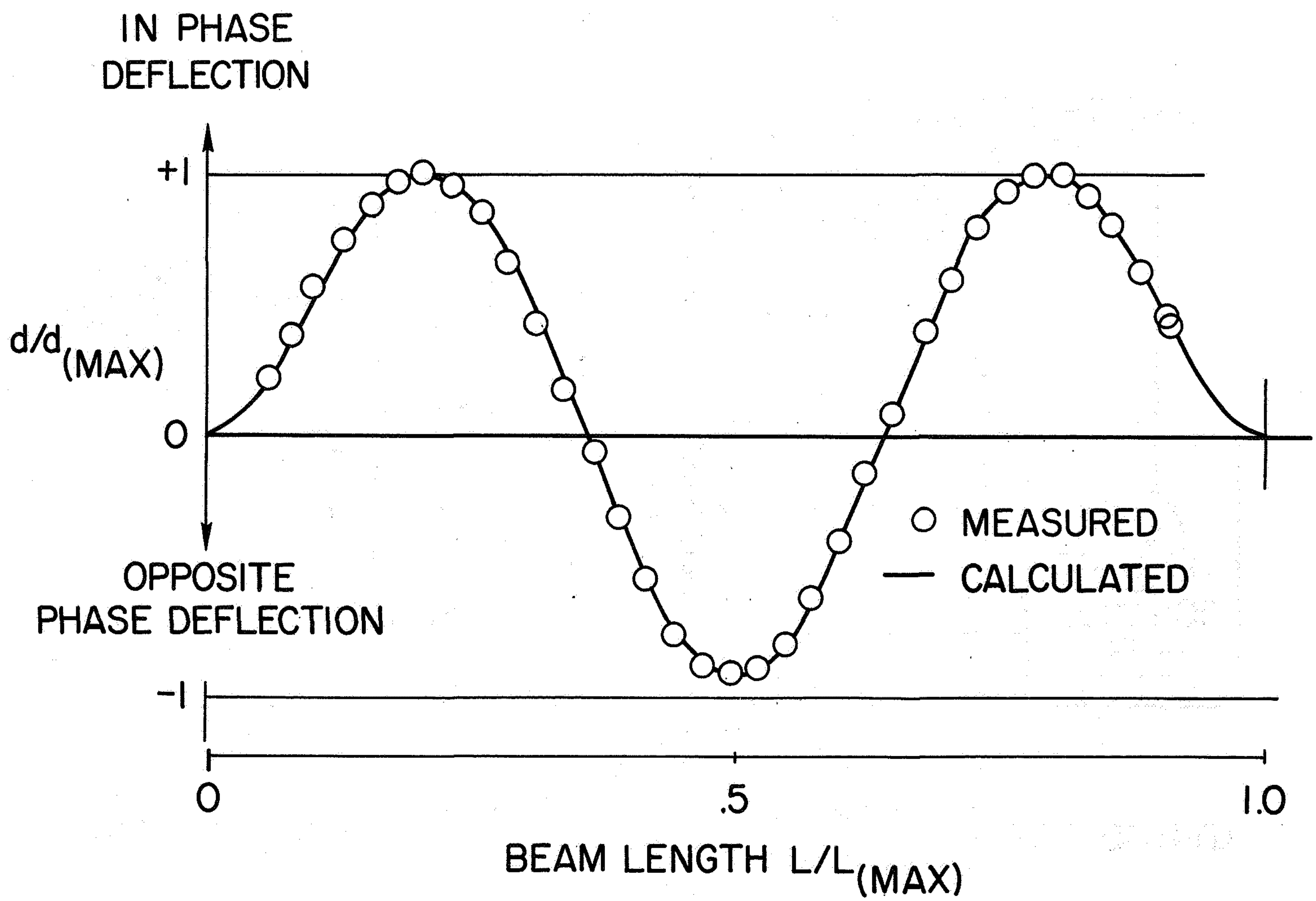

Figure 4.- Calculated and measured deflections.

PART II - APPLICATION TO CURRENT VIBRATION TESTING

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SUMMARY

Several automated transporting carriages have been designed and used to survey the vibrational modes of flat, conical, cylindrical, and complex curvature shell models. Circuitry has been provided which allows for several analog display formats and a method for orthogonal component separation. Some system response and sensitivity data, design criteria, typical test results, and views of the transporting carriages are presented and other possible applications of the system are discussed.

INTRODUCTION

In the first part of this paper, Mr. Flagge has described the circuitry for a position-servoed noncontacting displacement measuring technique. In order to be generally applicable to all vibration detection and measurement, the position-servoed displacement measuring transducer (hereinafter called probe) must be maintained essentially free from external excitation and be readily mobile. Obviously, these two requirements are in direct conflict because the major source of external excitation of the probe would be a result of moving the probe continuously about a vibratory member.

It is the purpose of this paper to describe several probe transporting systems which have been used and to present some of the design criteria. Circuitry is also described which provides for a variety of data display formats for the analog signal with and without orthogonal component separation.

System response and sensitivity, and typical test results will be presented for tests conducted on thin cylindrical, conical, and complex curvature shell models. And finally some possible alternate applications of this technique will be discussed.

TRANSPORTING CARRIAGE

Figure 1 is a pictorial view of the test setup. This figure shows: (1) the model, (2) the probe and trolley, (3) the track, and (4) the turntable. Each of these major components is discussed in subsequent sections and presented here for orientation purposes.

The cutaway view of the turntable is shown in figure 2. Some of the design criteria for this portion of the transporting carriage are: (1) very smooth motion is required and (2) a large base is necessary to increase versatility and to provide a stable platform. The turntable is rotated by a 1/4-hp high-torque ac motor through a gear reduction box. Rotational velocity of the turntable can be varied by changing the drive gear. The turntable is supported on twelve flat pieces of semirigid lubricating material (six above and six below the rotating ring) and is maintained concentric with the base by six curved pieces of the lubricating material. Shims located beneath these pieces of lubricating material are adjusted to obtained uniform fit and to vary the force required to rotate the table. This adjustment is necessary to insure low starting stiction and smooth rotation. It should be noted that the turntable can be oriented in any desired position including upside down.

Several different tracks have been used with this turntable in order that a variety of geometric model shapes could be investigated. Figure 3 presents schematic views of four tracks used for cylindrical, conical, complex curvature, and flat models; parts (a) through (d), respectively.

For cylindrical models the I-beam is mounted parallel to the longitudinal axis of the model and the circular track circumscribes the model. The probe-trolley travels along the track in defining the circumferential modes and the track travels along the I-beam in defining longitudinal modes. For the other models the trolley moves along the track in defining meridional modes and the track rotates about the model in defining circumferential modes.

A typical track cross section is shown in figure 3(d). All of the tracks have the same width and thickness. The rack is used by the probe-trolley for positive drive.

As shown in figure 3, this measurement technique possesses a high degree of versatility wherein the model geometry is used to define the geometrical requirements of the track.

Probably the most critical part of the transporting carriage is the trolley that supports the servomotor-probe system and travels along the track. One typical trolley design is shown in figure 4. The following parts are identified: (1) nylon rollers which roll along the track, (2) dc motor and drive sections, (3) potentiometer, (4) probe, (5) servomotor, and (6) servomotor suspension material. The design of the body, wheels, motor drive, etc., is relatively simple for fixed linear or circular tracks; however, for tracks such as for the tension skin model which has complex curvature, it is necessary to take into account the varying

relative displacements between the outer top wheels and the middle bottom wheels as the radius of curvature varies. The mass of the trolley should be kept as low as possible to decrease inertia transients when the trolley is moved.

The servomotor suspension method has a large effect on the overall performance of the deflection-sensing system. For best performance the suspension system should have a low natural frequency and high damping. Ideally the soft suspension would mechanically filter any high-frequency—small-amplitude vibrations transmitted through the transporting carriage and would rapidly damp out any low-frequency transients so that the servomotor would be essentially isolated from external perturbations. For the present system a foam material was selected that yields a 6-cps suspension frequency and has acceptable damping characteristics.

DATA PRESENTATION FORMATS

A mechanical system that transports the sensing elements so that continuous surveys can be made of the structural deformations of various model configurations and an electronic system that measures vibratory motion and produces an analog signal, both amplitude and phase sensitive, have been described.

The analog signal must be displayed in a manner that will permit the test conductor to realize the maximum benefit with the simplest display format. The following is a description of the data display capabilities which are currently in use.

A schematic representation of the data display capabilities currently being used and coordinate identification are shown in figure 5. This system employs several linear potentiometers, sine-cosine resolvers, and an associated operational amplifier for each. The potentiometers (each is assigned an identifying symbol) are used as variable-gain controls for the operational amplifiers. By utilizing only one power supply, each of the various signals can be related to any other. The symbols used in this figure are defined as follows:

s	trolley motion along the track
w	probe travel relative to the track
δ	analog signal
h and r	a voltage-dividing device which divides the output of the s amplifier into components corresponding to the instantaneous radius (r) and vertical height (h) (This divider may be fixed as for a cone or variable as for the tension skin.)
C	circumference
θ	polar plotting conditioner
ϕ	orthogonal component separation
1 and 2	summing amplifiers

As shown in figure 5, there is a wide range of formats readily available for automatically presenting the data obtained by the transducer. The person conducting the test thus has available to him, by the positioning of a switch, a series of display formats, one of which may be preferred for any given test condition. Two typical display formats will be presented in a later section.

SYSTEM RESPONSE AND SENSITIVITY

The system response and the system sensitivity is unique to its own assemblage because both values are dependent on a large number of variables such as transporting carriage stability, servomotor support material properties, transducer sensitivity, and overall system gain. However, a properly designed system can be adequately approximated by a single-degree-of-freedom spring-mass system wherein the mass of the servomotor probe and the suspension material spring constant determine the system natural frequency. This spring-mass system is excited primarily by the servomotor drive as the probe is maintained a constant distance from the model. The magnitude of the exciting force therefore is dependent on the servosystem gain; i.e., the restoring force increases as the gain increases.

A typical system response curve is shown in part (a) of figure 6. For this response test a constant amplitude displacement (dashed line) was provided by a hydraulic shaker (hereinafter called the exciter) over a frequency range of essentially 0 to 40 cps. The displacement output of the transducer, in rms volts (solid curve), was plotted as a function of frequency in figure 6(a). Figure 6(a) shows that for this test condition the servoed probe will follow the exciter in the frequency range 0 to 2 cps. This response characteristic is very important in the vibration testing of models suspended to approximate free-free end conditions but which have low frequency (<2 cps) rigid body motions. This response characteristic is valuable for evaluating model geometric deformations by monitoring the servoposition while traversing about the model. In the frequency range 2 to 14 cps the transducer output first rapidly increases to a peak value at 6 cps and then decreases to a constant value equal to the input. The peak value at 6 cps corresponds to the natural frequency of the spring-mass system. The frequency response of the system becomes flat at 14 cps indicating that the servosystem is stable and maintaining the transducer at a constant distance from the exciter mean position.

The system sensitivity is very dependent on the type of transducer used; that is, the larger the transducer the larger the minimum distinguishable amplitude. Figure 6(b) illustrates a typical sensitivity curve for the same probe system used in the response test in figure 6(a). For illustration purposes, however, this test was conducted with the exciter servocontrolled to maintain a constant linear velocity. The exciter velocity selected was that which occurs for a 1 g peak acceleration at 100 cps. In figure 6(b) the displacement output is shown as a function of frequency. This curve covers a range of displacements of the order of 400 to 6500 microinches over a frequency range of 30 to 500 cps. Comparison of measured and theoretical values of displacement at discrete frequencies indicate an accuracy of ± 2 percent for this system. It should be noted that smaller deflections and/or higher frequencies would require a transducer with a greater sensitivity; i.e., volts output per inch displacement, in order to maintain or improve the accuracy of deflection measurements.

It should be noted that these values were obtained in a basically static condition; i.e., probe-trolley fixed, and are therefore free from any perturbations arising from transporting-carriage motion.

TYPICAL TEST RESULTS

Typical test results are shown in figure 7. The results were obtained from tests of a 0.025 inch thick, 120° included angle aluminum alloy conical frustum having a 4-foot maximum diameter. The cone was clamped at the minor diameter of 8 inches and the exciting frequency was 21 cps. The two sets of curves are shown to illustrate two methods of data display. The set of curves on the left (figs. 7(a) and 7(b)) are for linear display of probe output during a traverse down the slant height of the model and probe output around the circumference of the model at three values of radius. The curves on the right (figs. 7(c) and 7(d)) are for the same conditions but are displayed with orthogonal component separation and in polar form. It can clearly be seen that either method of presentation provides an easy method for determining both longitudinal and circumferential mode numbers and also that nodal patterns can be readily constructed.

APPLICATIONS

The system that has been described has many potential applications both in its present form and in the many variations which can be easily realized. We have used this system in whole or in part for obtaining vibration data of thin shells having flat, cylindrical, conical, and complex curvature configurations. In addition, tests will be conducted using a similar system on such large models and vehicles as the 1/10-scale Saturn V model and the full-scale Thor-Agena launch vehicle.

This system also is well adapted to measuring damping where the high gain available permits measurements of very low amplitudes.

Another application of this technique is in panel flutter and panel response work at both atmospheric and reduced pressures. A typical test setup for such a test is shown in figure 8. The probe carriage here is much more massive than in the shell tests and the probe motion is from point to point rather than continuous. The analog signal from the transducer is digitized and stored in punched cards for later analytical analysis. The analog-digital converter and card punch are shown in the insert. The type of data recorded include reference frequency, response frequency, response phase relative to the reference phase, and response magnitude.

CONCLUDING REMARKS

A noncontacting displacement measuring system has been developed and shown to be very capable of accurately defining the dynamic responses of thin shell models. The system basically consists of three discrete parts, any of which can be easily altered for specific jobs. These parts are: (1) a position-servoed displacement sensitive transducer, (2) a mechanical transporting carriage for moving the probe about the model, and (3) circuitry which provides a variety of techniques for using the analog signal for direct readout of the results obtained.

The system has been shown to have excellent frequency stability and to exhibit very high accuracy in terms of the amplitude measured.

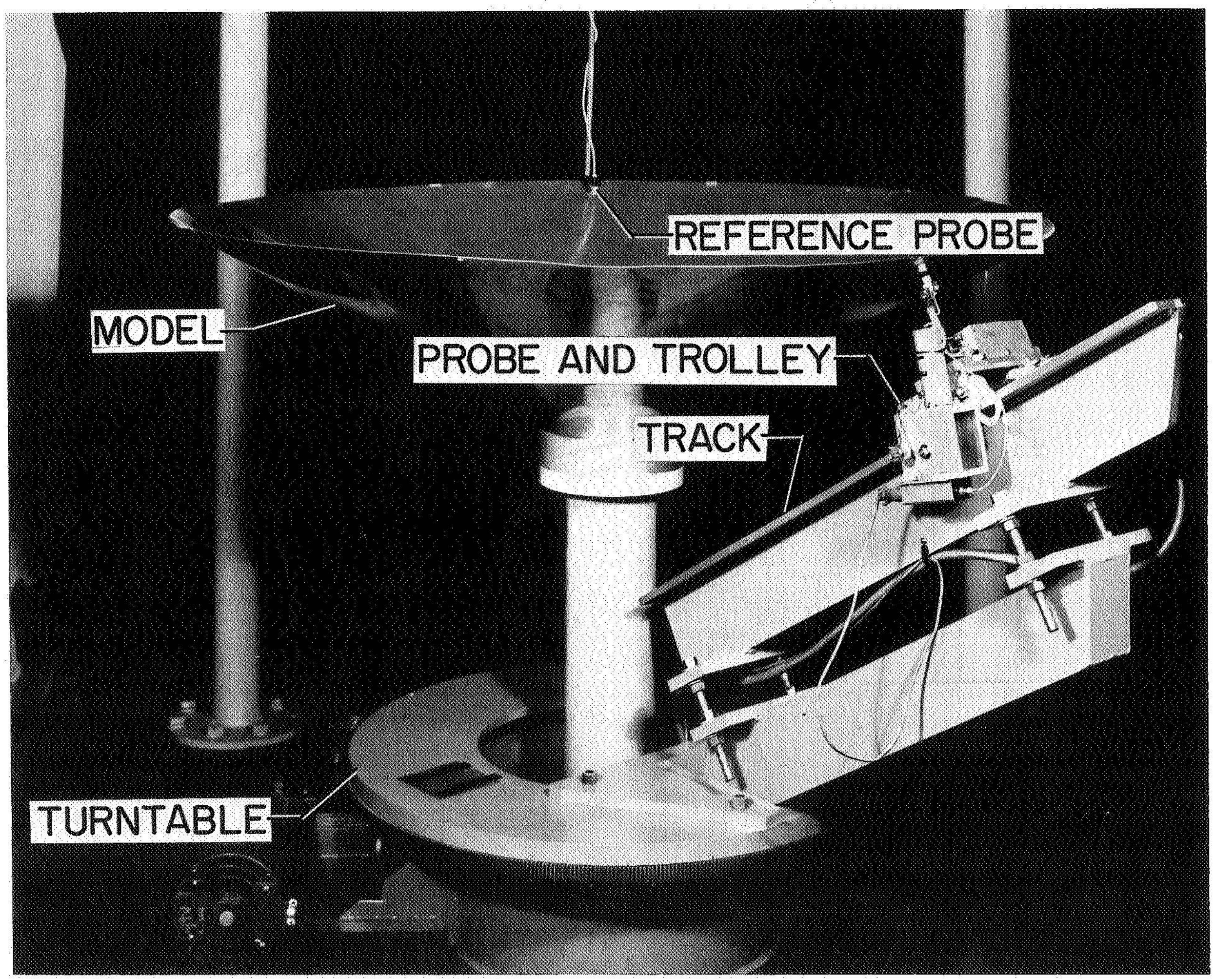

Figure 1.- View of test setup.

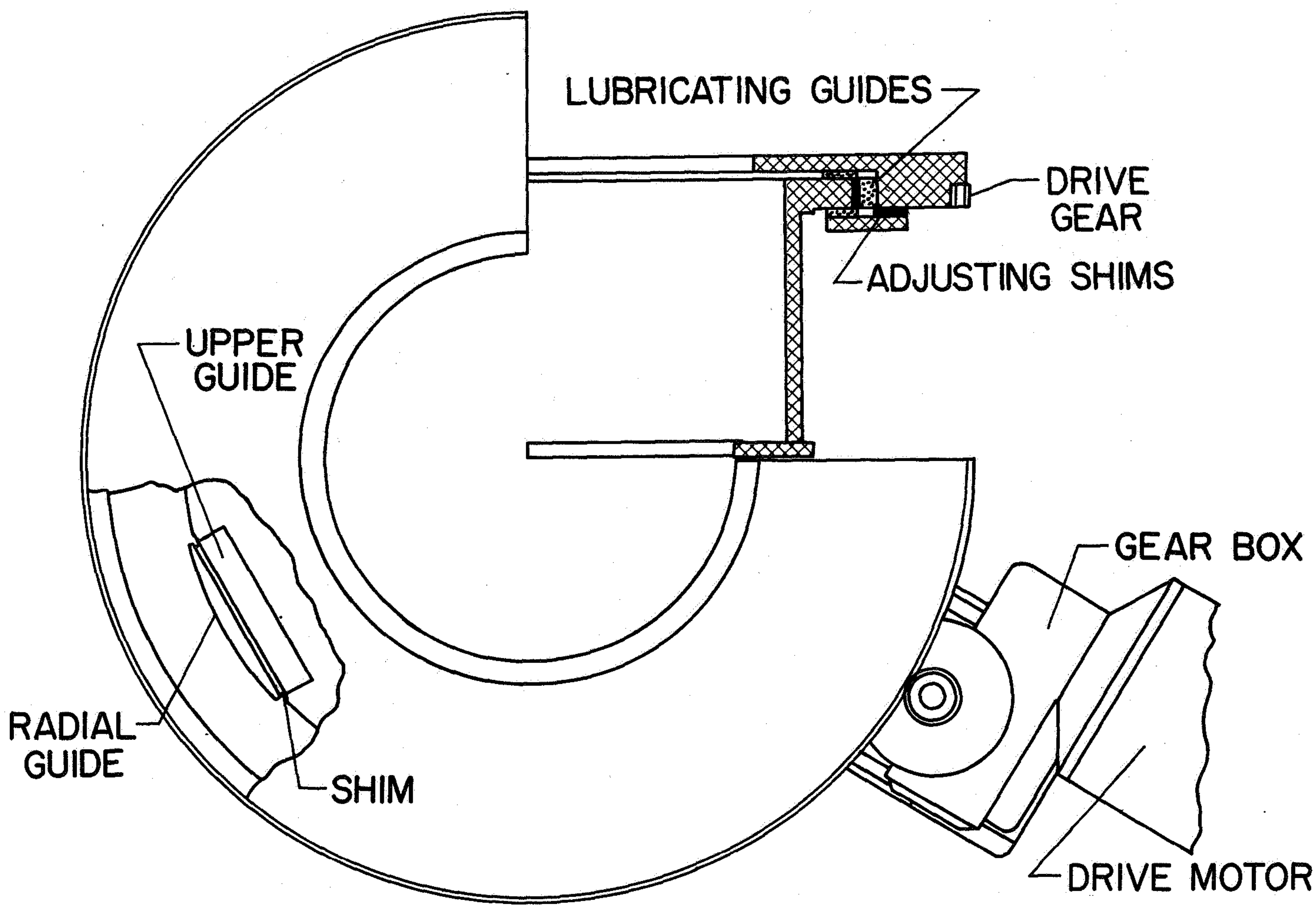

Figure 2.- Schematic view of turntable.

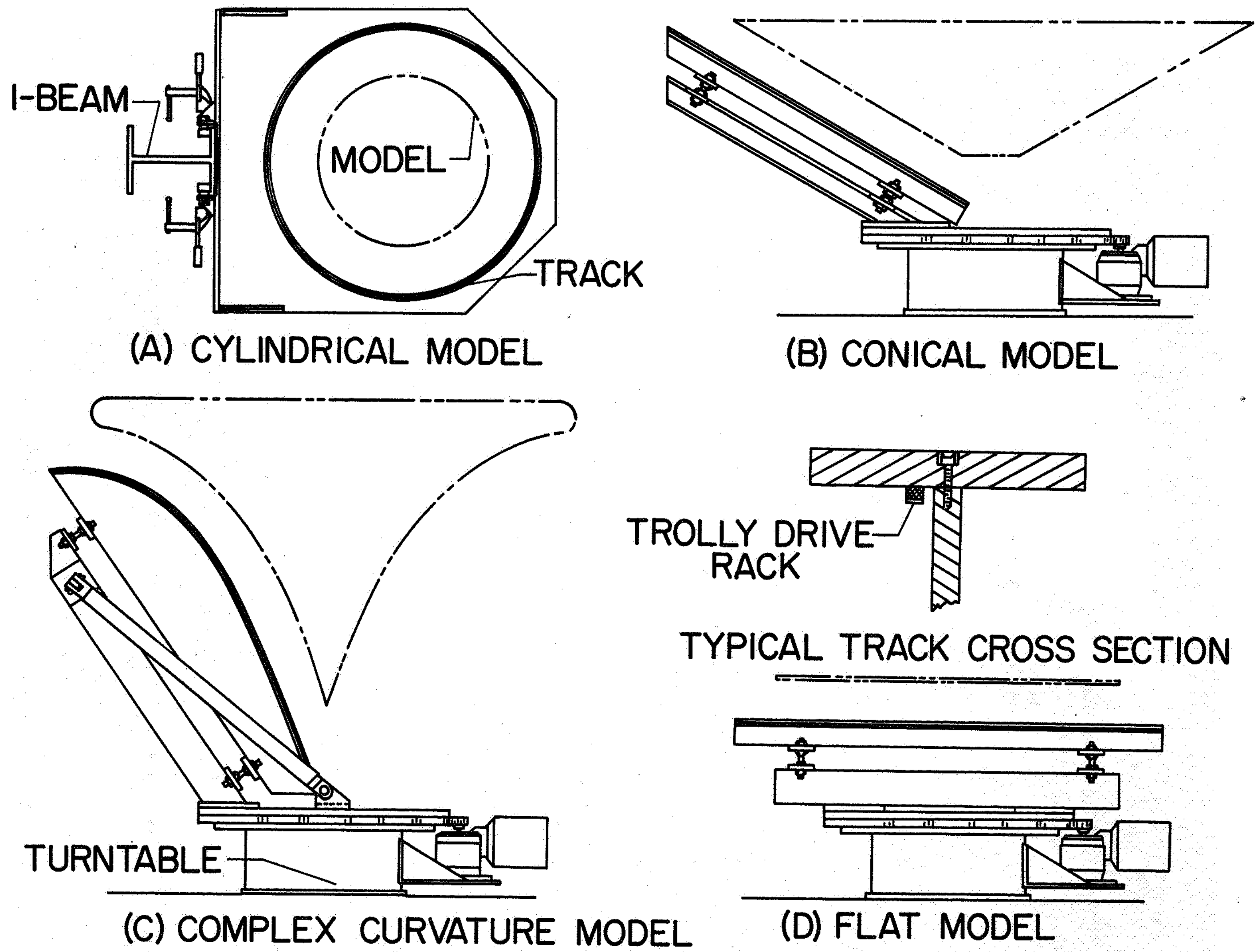

Figure 3.- Schematic views of tracks.

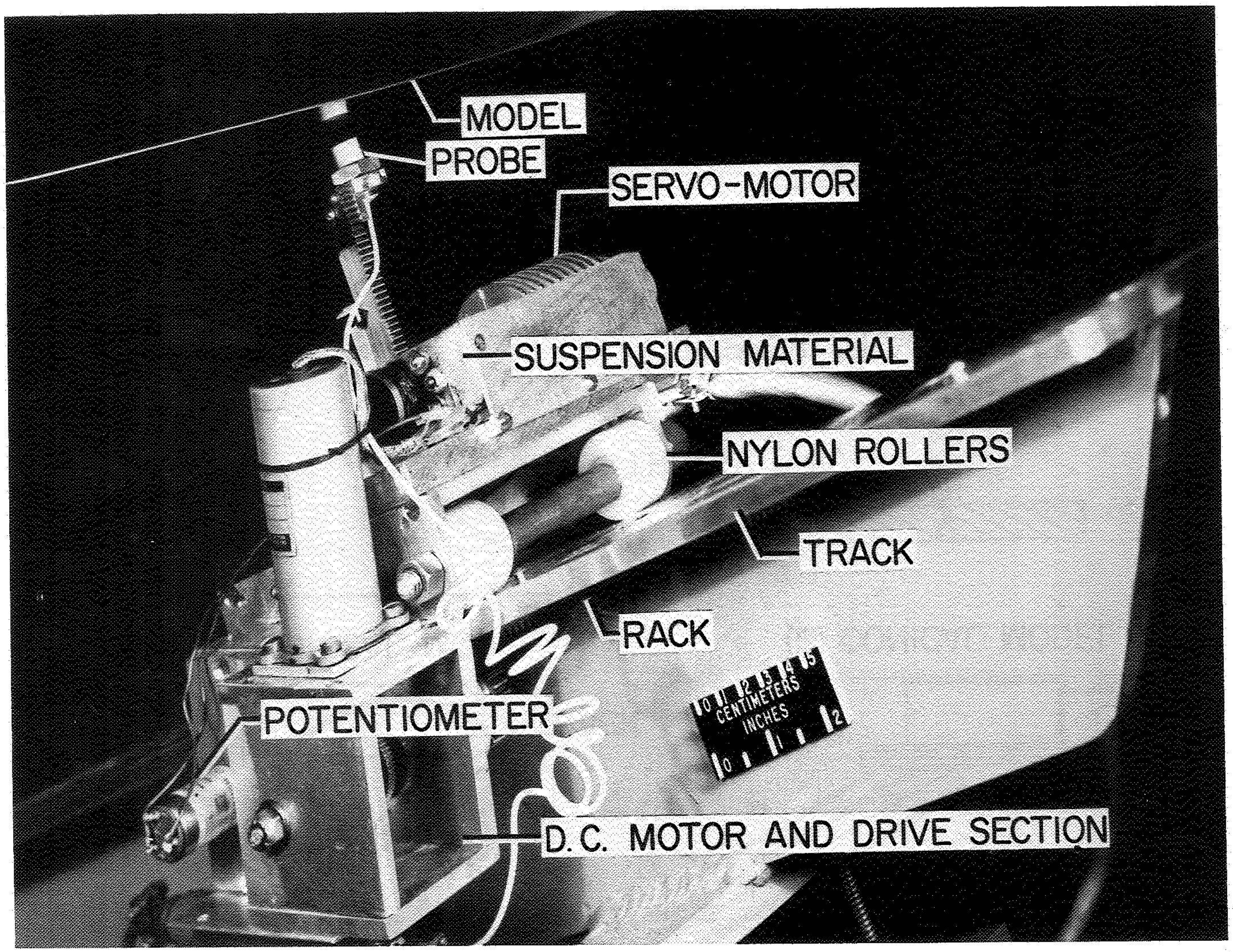

Figure 4.- View of trolley and servomotor-probe system.

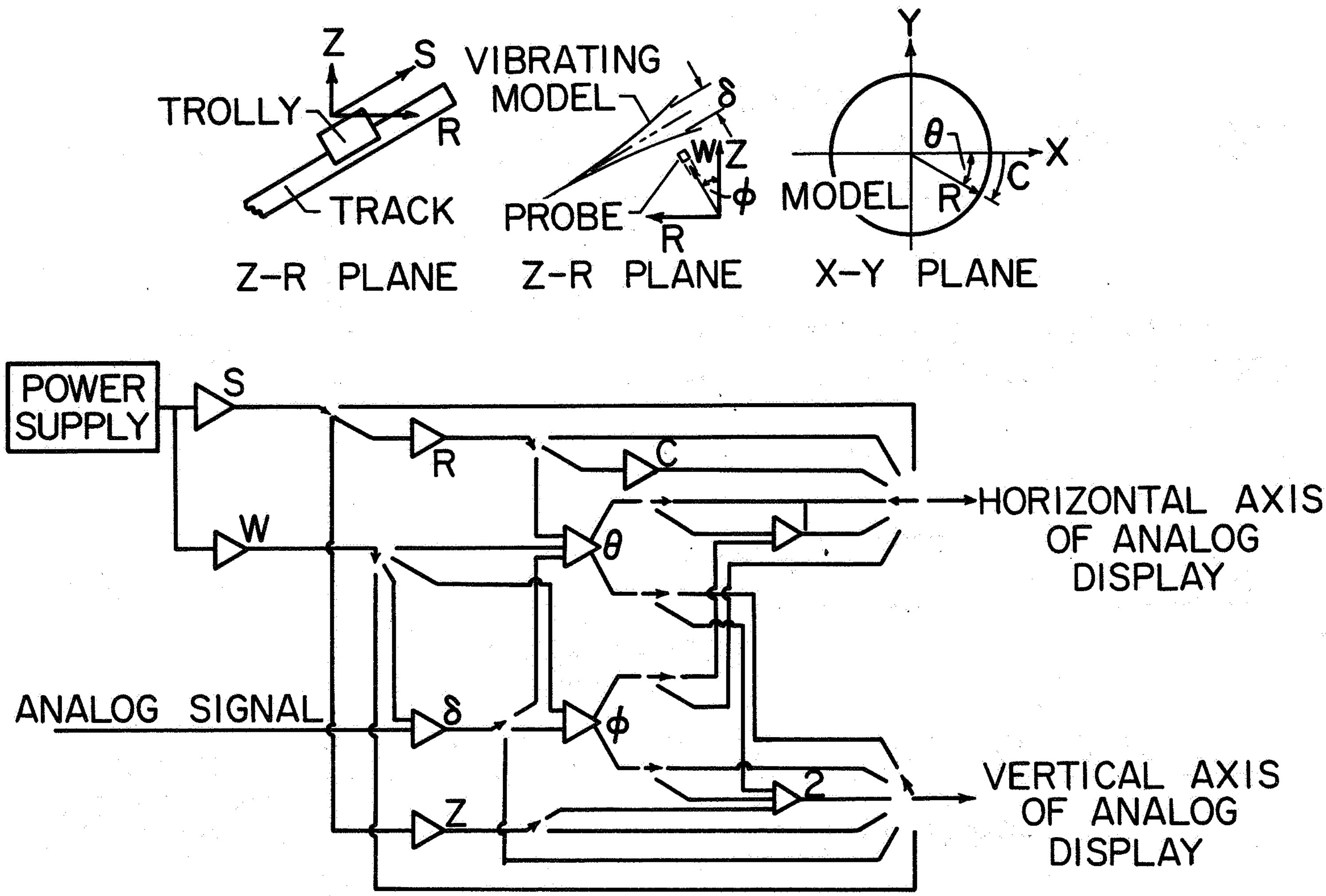

Figure 5.- Schematic presentation of data display formats.

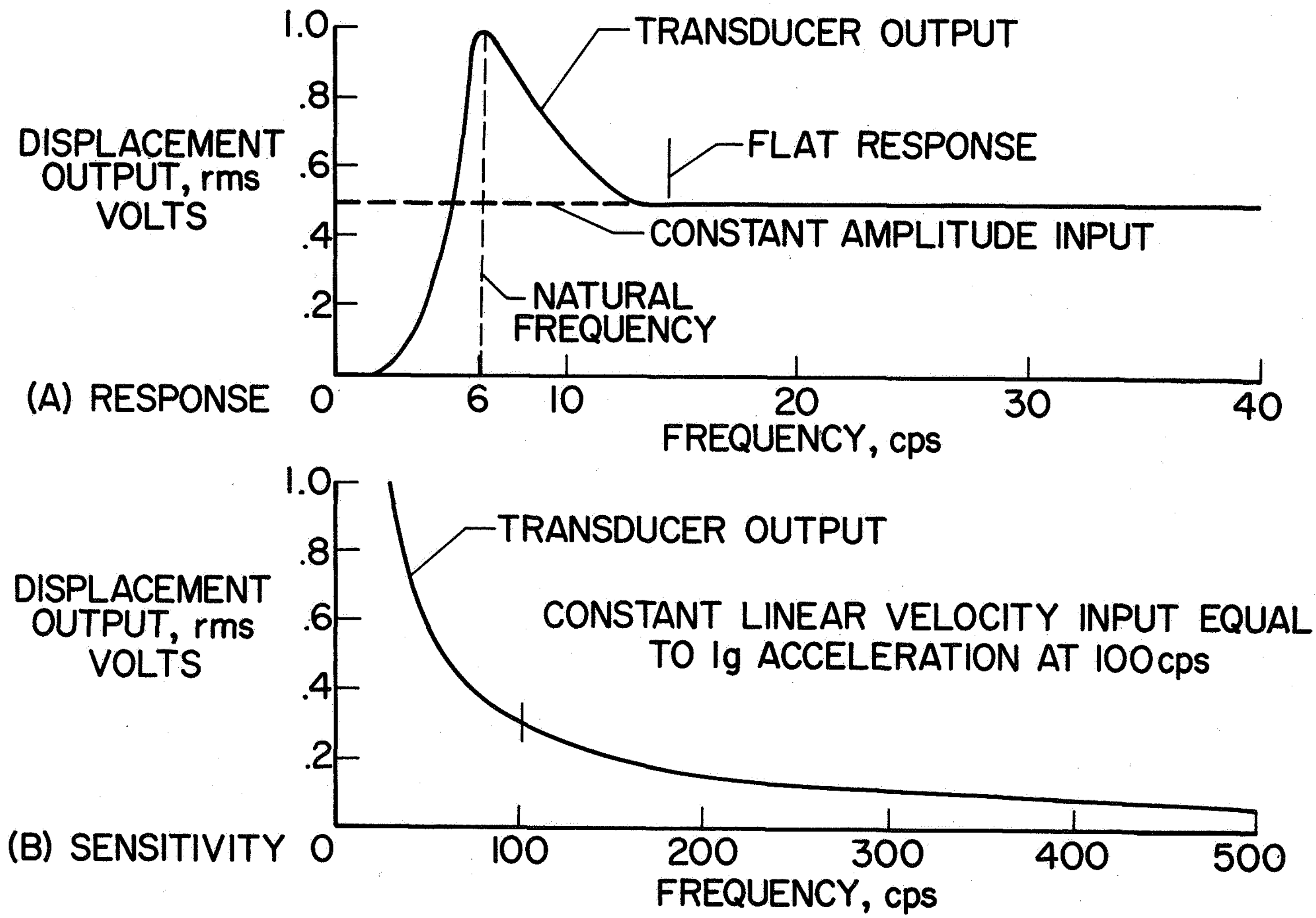

Figure 6.- System response and sensitivity.

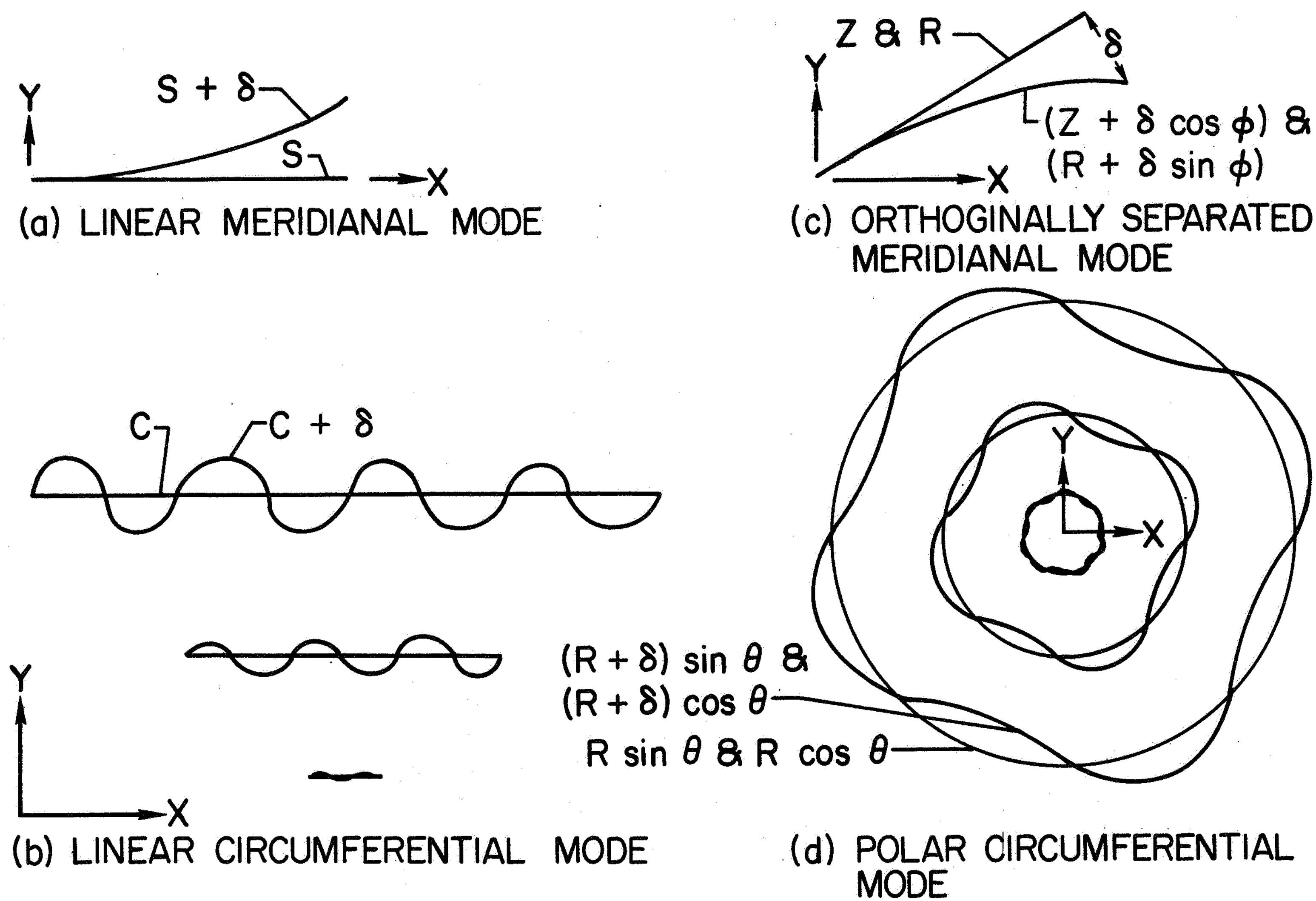

Figure 7.- Typical test results.

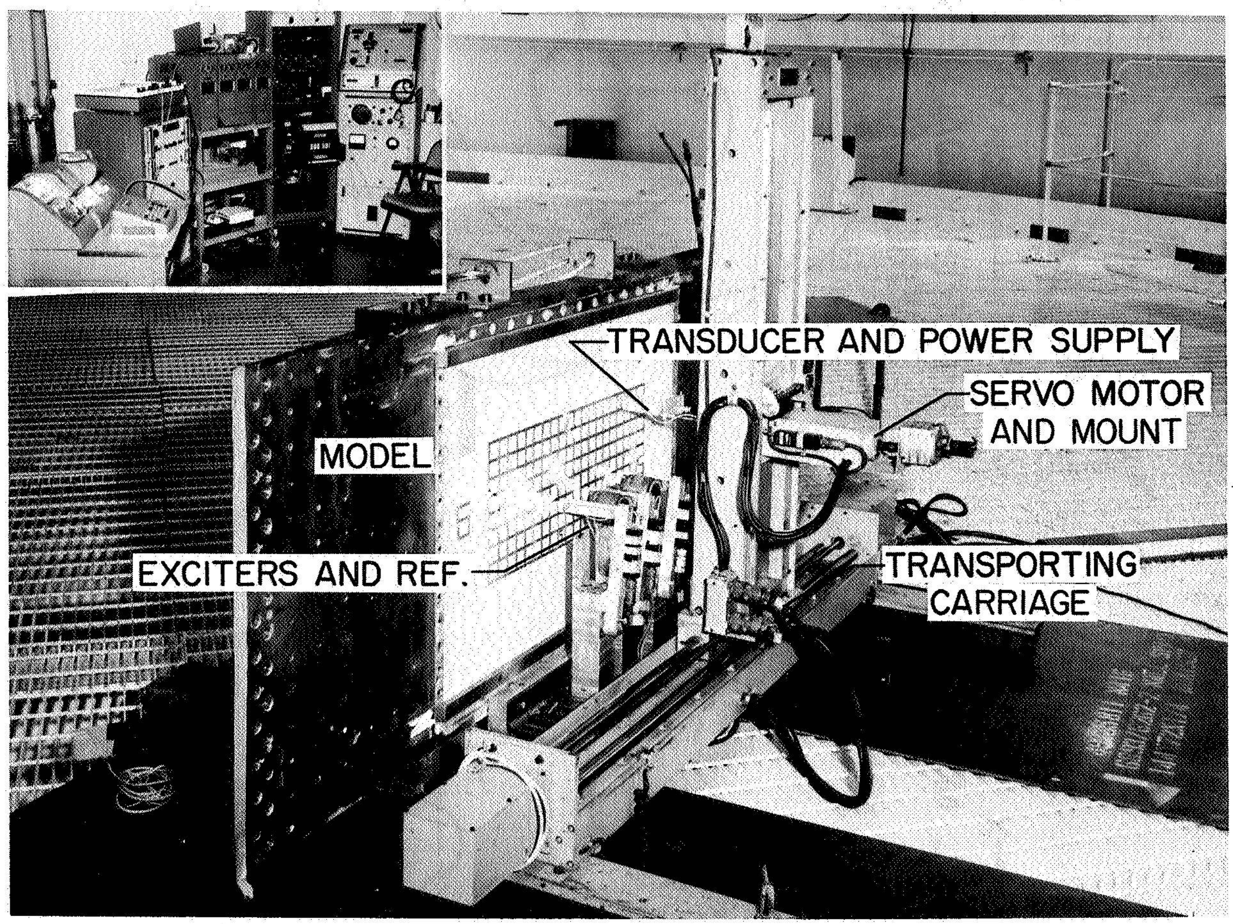

Figure 8.- View of panel response test setup.